Airborne Dust and Sediment Measurements in Agricultural Fields

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Abstract

Spatial and temporal variations of soil conditions across agricultural fields can produce field-scale variations of soil particle entrainment, wind erosion, dust transport and deposition. We describe a field evaluation and sampling system designed to measure airborne dust / sediment and other wind erosion factors. Soil surface conditions are monitored before and after wind erosion events. Hourly averages of sediment flux are measured at five to eight elevations at several locations in the field. Particle impact frequency is monitored near sediment flux sampling points. Dust measurements are made using a Minivol[1] air sampler located at various heights on a 10 m tower. Important meteorological data are obtained from the same 10m tower and a portable 2 m tower. We also describe a device for laboratory measurement of dust produced from field soils.

Introduction

Wind erosion is an international problem affecting air, water and soil quality, food production, transportation, telecommunication and electrical systems, and human, plant and animal health. Although USDA-NRCS estimates wind erosion on cropland decreased nearly 25% from 1982 to 1992, about 0.8 billion metric tons of soil were removed from cropland by wind erosion in 1992 (USDA-NRCS, 1994). Pimentel *et al*. (1995) ascribed billions of dollars of annual economic losses in the USA to wind erosion.

Wind action entrains particles from the soil surface, causing them to move. Some are extremely heavy or large and merely creep or roll along the soil surface. Smaller grains bounce (saltate). These two classes of particles do not move great distances from their source of entrainment. However, the finest grains of dust are suspended by the wind and may be carried great distances from the source.

Recent advances in sampling technology have provided many new devices and methods to measure wind erosion and sediment and dust transport through the atmosphere. Several of these instruments are used by our research unit to study agricultural fields as dust sources. One inexpensive, reliable sampler to measure particles bouncing above the soil surface in saltation, the BSNE, was described by Fryrear (1986). An electronic device to measure the number of saltating particles, the SENSIT, has also been developed (Stockton and Gillette, 1990). These instruments were not designed to measure fine particulates moving in suspension. Since the US EPA implemented the PM_{10} air quality standard (airborne particles $\leq$ 10
been developed to measure fine aerosols. Chow (1995) presented a thorough review of these devices.

Sampling devices to measure airborne sediment and dust are important but tell only part of the story. Many factors affect wind erosion and dust transport. The most important factors include the soil surface conditions (such as surface roughness, aggregation, crusting, etc.), vegetation or other soil cover, and meteorological factors. Knowledge of all of the factors that affect wind erosion in the field is necessary to fully understand the process. We have developed a relatively inexpensive sampling system to measure sediment and dust transport and important soil and meteorological factors associated with wind erosion. In this paper we will describe the system's components and briefly discuss some of our data analysis techniques.

Soil/Site Characteristics

The physical characteristics of an agricultural field affect its wind erodibility and should be documented prior to and after the erosion event (at several locations in the field) in order to determine how erosion has modified the field. Several of these characteristics were described in detail by Zobeck (1991b). We recommend measuring or noting the following:

1. Surface microrelief (roughness)
2. Surface residue or other cover
3. Dry aggregate size distribution
4. Dry aggregate stability
5. Soil crust properties

A composite sample of the soil surface horizon is collected prior to any erosion to determine its intrinsic (relatively unchanging) soil properties. The intrinsic soil properties generally measured include particle size distribution, calcium carbonate and organic carbon content. After an erosion event, the saltating material may be sampled separately to compare its properties with those of the parent soil.

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[1]Names are necessary to report factually on available data; however, USDA neither guarantees nor warrants the standard of the product. The use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

Surface Microrelief

Soil surface microrelief refers to relatively small-scale surface features or topography produced by tillage or other activity. Surface microrelief is important to wind erosion because it affects the aerodynamic roughness (z_o) of the site. In agricultural soils, tillage tools often create an oriented roughness parallel to the direction of tillage. In addition, the random orientation of clods or aggregates produced during tillage creates a random roughness. Wind erosion is sensitive to the effects of both oriented and random roughness (Armbrust *et al.*, 1964; Fryrear, 1984) so we quantify random and oriented roughness-related parameters.

A relatively simple method of determining random roughness was suggested by Currence and Lovely (1970). In this method, the standard deviation of surface elevation measurements is calculated after correcting for the effects of surface slope and oriented roughness. Allmaras *et al*. (1966) used the logarithm of elevation measurements and removed the upper and lower 10% of measurements before calculating random roughness. These methods produce slightly different results. We suggest using the Currence and Lovely (1970) method, since removing the upper and lower 10% of measurements may remove important site variation.

Quantifying microrelief using random roughness alone is not adequate because wind erosion is sensitive to the effects of random and oriented roughness. An index called the cumulative shelter angle distribution (CSAD) was developed to overcome this limitation . The CSAD will simultaneously account for the effects of both random and oriented roughness (Potter *et al.*, 1990) and can be used to estimate the fraction of the surface exposed to saltation. We have found that the CSAD varies considerably with observation number. Research is now underway to standardize the CSAD calculation procedure.

Many devices have been used in the past to measure microrelief (Zobeck and Onstad, 1987). Usually, microrelief measurements are made by collecting many elevation readings using some type of transect or grid pattern on the soil surface. A grid pattern is particularly useful when calculating the CSAD because elevation measurements must be collected using equally spaced observations made parallel and perpendicular to the tillage direction. In addition, a grid pattern made parallel with the tillage direction makes it possible to use regression procedures to remove the effects of oriented roughness when calculating random roughness. In our studies, we use a laser-based system capable of collecting a large number of surface elevation measurements on a one-meter square plot (Huang and Bradford, 1990).

Saleh (1993) suggested using a chain method to describe surface microrelief. A roller chain 1m-long is stretched along the soil surface and measured. The roughness measurement is the ratio of the chain
soil surface to the original chain length. The low cost, portability, and ease of this method make it attractive for field personnel. We compared this method with calculations of random roughness using 400 observations in a 25 mm grid over a 1m-square plot. The correlation of the two methods was not high ($r^2 = 0.46$), but they did have similar trends. Use of the chain method is appropriate when relative estimates of microrelief are needed and precise calculations of random roughness and CSAD are not required.

Surface Cover

Surface cover is another important site characteristic that we quantify in our field studies. Vegetation, gravel, desert pavement or other nonerodible matter covering the soil surface absorbs some of the shear stress imparted by the wind, protecting it from the erosive impact of saltating particles (Lyles *et al*., 1974). Fryrear (1985) has shown that a cover of 20% reduced soil losses 57%, and 50% cover reduced soil losses 95%.

We measure surface cover using a photographic method. A 1m-square frame is placed on the soil surface, and a slide photograph is taken from directly above the frame. The slide is then projected on a grid of 100 points equally spaced over the entire frame. Percent cover is equal to the number of points touching the cover. An alternative procedure is a line-transect as described by Steiner et al., (1994). A line-transect is made by stretching a tape or string with 50 or 100 markings across the field and counting the number of markings touching surface cover. The surface cover fraction is the number of markings touching cover divided by the total number of markings observed.

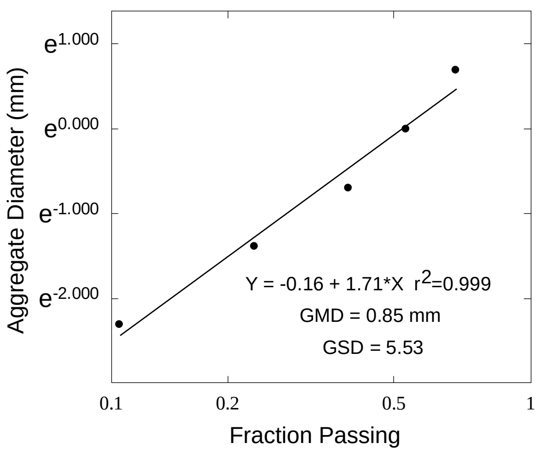
Dry Aggregate Size Distribution

The dry aggregate size distribution (DASD) is an important soil property that we measure for loose, non-crusted soils. The DASD refers to the relative amount of surface soil aggregates, by size class, as measured by dry sieving procedures (Chepil, 1942). The effect of DASD on wind erosion was first described by Chepil (1951). Particles of mineral soils greater than 0.84 mm diameter are considered nonerodible by wind.

Research has shown that the distribution of aggregates on the soil surface is generally log-normal and can be adequately described by the geometric mean diameter and the geometric standard deviation (Gardner, 1956). We measure DASD by dry sieving a 5 kg air-dried sample of surface soil in a rotary sieve (Chepil, 1942). We then regress the natural logarithm of sieve diameter on the normal probability of the fraction of soil passing that diameter (Fig 1). The normal probability is determined using the PROBIT function of SAS[1] software (SAS, 1990). The geometric mean diameter is the antilog of the sieve size at 50% passing. The geometric standard deviation is described by the equation (Allen, 1981):

$$\text{GMD/Diameter at 84\% passing} \qquad [1]$$

Fig 1. Logarithm of aggregate size versus fraction passing sieve of the specified diameter. Fraction passing axis has a probability scale.



Dry Aggregate Stability

Dry aggregate stability (DAS) refers to the resistance of soil aggregates to breakdown from physical forces (Skidmore and Powers, 1982). We measure DAS because studies have shown that abrasion of blowing sand grains against aggregates correlates well with a measure of dry aggregate stability called the crushing energy (Hagen *et al*., 1992). Dry aggregate stability is measured for surface soil aggregates of approximately 20 mm diameter using a crushing energy meter (Fig 2; Skidmore and Powers, 1982). Fifteen aggregates are collected from 3 or more different sites in the field. Each aggregate is crushed to a specified endpoint; the crushing energy is determined by integrating the area under the curve relating force of crushing versus distance of crushing. We collect samples only prior to the erosion event because we assume aggregate stability does not change appreciably during the wind erosion sampling period. In studies spanning several months, we recommend measuring aggregate stability at least monthly.

Soil Crust Properties

In newly tilled soils, the surface is loose and cloddy. But after about 0.01 m rainfall, a relatively thin consolidated zone, called a crust or seal, often forms. Although crust properties vary considerably depending on intrinsic soil properties, they can have a significant impact on the wind erodibility of agricultural fields. Several crust properties believed to affect wind erosion and dust production have been described by Zobeck (1991b). In our studies the crust properties we measure or estimate include crust thickness, stability, cover fraction, and loose erodible material.

Crust thickness is very difficult to estimate because it varies considerably within a single field. Often a thin crust produced by raindrop impact is found on ridges, and a thick, laminar crust produced by running water is found in furrows. We measure crust thickness with a hand-lens and ruler on at least 30 samples.

Fig 2. Soil aggregate crushing energy meter.

Crust stability, in the context of wind erosion, refers to the ability of crusted soils to withstand impact abrasion by saltating particles during erosion events. Surfaces with very stable crusts resist abrasion better than surfaces with weak crusts. We have no recommended method of measuring crust stability in the field because field crust samples are generally too fragile to use in a crushing energy meter. Estimates of crust stability may be made by applying equations developed via wind tunnel studies (Zobeck, 1991a)

The cover fraction refers to the fraction of the soil surface, on an area basis, covered by crust. In most soils, large aggregates remain intact under the force of light to moderate rainfall and only break down after a considerable amount or very heavy rain has fallen. As the larger clods break down, a crust may form between the large aggregates or other stable objects, such as rock fragments. The cover fraction quantifies the crust formed and can be measured using the line-transect method (Steiner et al., 1994).

Loose erodible material (LEM) is defined as loose, unconsolidated soil material less than 0.84 mm equivalent diameter (Chepil, 1951) exposed on the soil surface. Loose erodible material is measured only when a crust is present. When a crust is not present, as in newly tilled fields, the erodibility is better defined by the DASD. We measure LEM using a vacuum system designed for this purpose (Fig 3, Zobeck, 1989). Representative areas within a dry field are vacuumed, and the samples are sieved and weighed. LEM mass is reported on an area basis. The cover fraction of LEM is also measured using the line-transect method.

Fig 3. Fast-Vac system to measure loose erodible material.

Airborne Sediment and Dust

Measurements and Instrumentation

Our current system for measuring airborne sediment and dust is similar to that described by Fryrear *et al.* (1991). We have added instruments to measure PM_{10} and made other refinements described here. We measure airborne sediment at eight or more locations across the field parallel to the wind direction. Five or eight sampling heights, using two types of passive samplers (Figs 4 and 5), are measured at each location. A near-surface sampler (designed by Fryrear and Stout) collects creep-saltation material from three inlets at 0-3 mm, 3-9 mm, and 9-20 mm above the surface (Fig 4). All openings are 5.5 mm wide. A predecessor design of this sampler was tested and found to be highly efficient (Stout and Fryrear, 1989).

We use a vertical array of five BSNE samplers to sample at heights above 20 mm (Fig 5). The BSNE samplers pivot into the wind, capturing entrained particles at heights of 0.05, 0.10, 0.25, 0.50 and 1.0 m. In some studies the two highest samplers were deployed at greater heights. The inlet areas for the two lowest samplers are about 200 mm^2 and are about 1050 mm^2 for the three highest samplers. The two lowest BSNE samplers have a smaller sampling area because much more sediment is moving close to the soil surface and larger openings are not necessary. In some locations the near-surface samplers are not installed and only 5 heights are sampled using BSNE samplers.

The BSNE sampling clusters are highly mobile. We anchor the base of the cluster using a 0.3 m x 0.3 m by 0.12 m thick steel plate weighing about 9.3 kg (Fig 5). The sampler cluster can be easily moved yet does not fall over in strong winds. The exact siting of the samplers across a field will depend on field characteristics. In highly erosive soils we recommend separating clusters using a geometric progression of distance with the first samplers separated by about 35 m. Careful spacing of the samplers and locating the eroding field boundary relative to wind direction are critical in studies of saltation and wind erosion flux across the field.

Fig 4. Near-surface creep/saltation sampler.

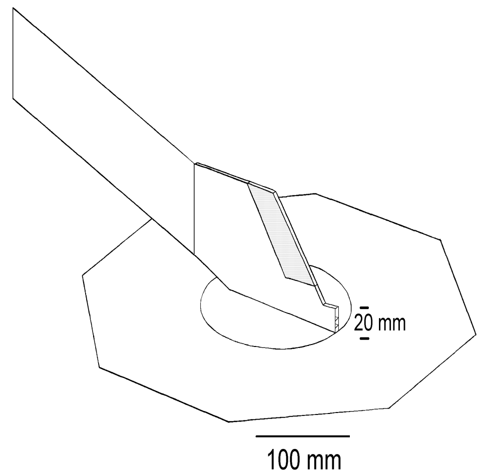
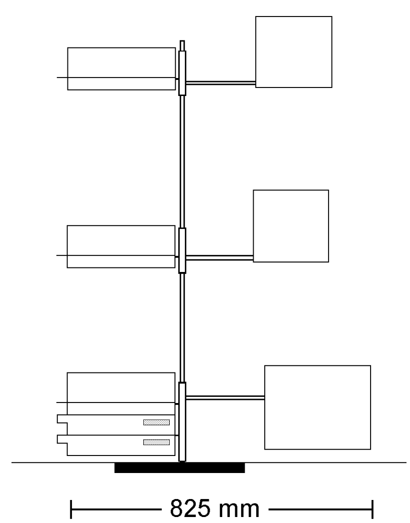
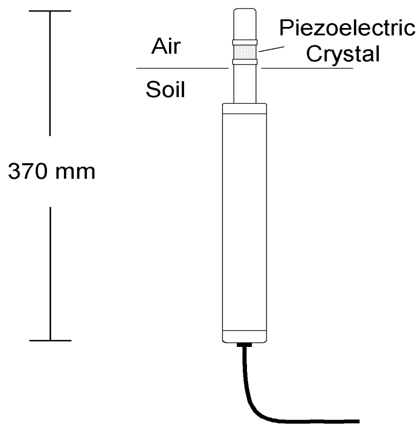


Fig 5. BSNE sampling cluster.



Erosion activity is monitored using a SENSIT[1] device (Fig 6). The SENSIT provides a pulsed signal proportional to the number and momentum of particle impacts on a ring-shaped piezoelectric crystal 0.25 m diameter and 0.125 m high (Stockton and Gillette, 1990). The crystal can be placed at the soil surface to monitor the erosion threshold.

Fig 6. SENSIT particle impact sensor.



We monitor PM_{10} with Minivol[1] air samplers (produced by Airmetrics, Inc). Low-volume intake samplers such as the Minivol may be better suited to the high wind conditions experienced during dust storms than other types of samplers. The PM_{10} samplers are mounted on a 10 m tower located on the downwind end of the study field. Our current setup places samplers at four heights on the tower. The samplers can be programmed to sample for various durations. Our samplers are wired to manual switches to better coordinate PM_{10} sampling with saltation sampling using BSNE clusters.

Wind velocity and other meteorological factors are also measured before and during erosion events. Wind velocity is monitored in the field using an array of cup anemometers mounted at heights of 0.2, 0.4, 0.8, 2.0, 4.0, and 10.0 m. Wind vanes are placed at 2 m and 10 m. The four lowest wind velocity measurements are taken from a separate small tower, and the highest two anemometers share the 10 m tower with the Minivol samplers. Air temperature is measured at 0.2, 0.4, 0.8, 2.0, and 10.0 m; relative humidity and solar radiation are measured at 2 m height.

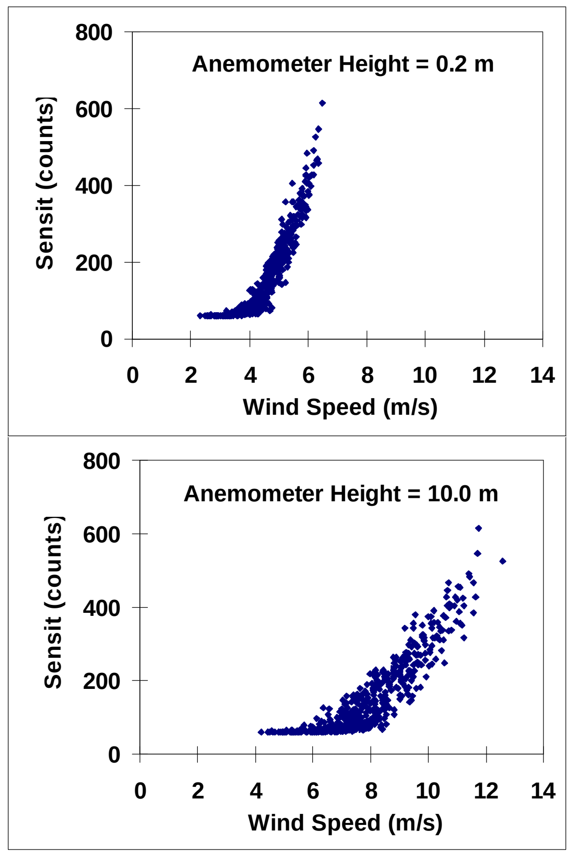
Analysis of Sediment Data

Particle Impact Sensor

The SENSIT provides an excellent means of monitoring the wind speed at which particle movement begins (threshold wind speed). The value for the threshold wind speed varies with several factors including particle size and surface conditions. Studies in different environments have found that threshold wind speed decreases during the course of significant dust storms (Stout and Zobeck, 1995; Gillette *et al*., 1996). Much more detail on the use of SENSIT to estimate threshold wind speed will be presented later in this conference (Stout and Zobeck, 1996).

Since wind speed changes logarithmically with height, estimates of threshold wind speed should always state the height at which wind measurements are taken. The importance of wind speed variation with height is illustrated in Fig 7, representing the same set of SENSIT data compared with wind velocity taken at two different heights.

Fig 7. SENSIT readings versus anemometer height.



Horizontal Mass flux

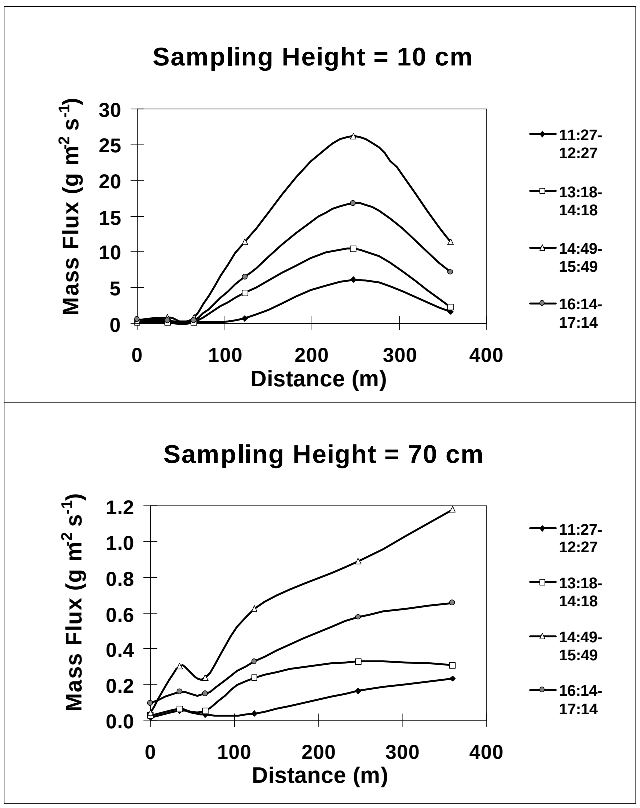
The samplers located along the direction of the wind allow us to calculate the horizontal flux of sediment across the field. The variation of horizontal mass flux at a specific height above a uniformly erodible surface was derived by Stout (1990b) as:

$$\frac{f(x,z)}{f_{max}(z)} = 1 - e^{-x/b(z)} \qquad [2]$$

where $f(x,z)$ is the horizontal flux at length x from the nonerodible boundary at height z, $f_{max}(z)$ is the maximum flux for the field at height z, and b(z) is the distance (at height z) at which *f(x,z)* attains a value of 63.2% of $f_{max}(z)$. Fryrear *et al*. (1991) redefined *f*(x,z) of Eq. 2 as the total mass flow of sediment (q) to describe the horizontal distribution of q using a similar expression.

The ideal horizontal distribution of mass flux expressed by Eq 2 is often not realized in the field because the surface is complex. Above complex soil surfaces, mass flux may vary in a complex manner, as illustrated in Fig 8. Each curve on this figure illustrates a one-hour measurement period during

Fig 8. Horizontal flux of sediment measured for four hours at two heights.



a dust storm that occurred on April 14, 1994 at Wolfforth, Texas. The most erosive period occurred during the third hour of observation. Note the difference in scale of mass flux at the two heights shown. The flux measured at 0.1 m was about 20 times the flux measured at 0.7 m. At a height of 0.1 m, deposition occurred at a distance approximately 250 m from the nonerodible boundary, as indicated by the downward trend of the curves at that position. At a height of 0.7 m, this downward trend is not apparent.

The differences in horizontal flux behavior at the two heights can be attributed to differences in the dominant mode of transport at each height. At 0.1 m, most material is in saltation and greatly affected by local microrelief. At 0.7 m, most of the sediment is in suspension and does not show the deposition evident at 0.1 m height.

Vertical Mass Flux

The vertical mass flux profile within the fully-developed surface layer can be described by a simple power-law function of the form (Stout and Zobeck, 1995):

$$\frac{f_{max}(z)}{f_0} \quad [1 \quad \frac{z}{}]^{2} \qquad [3]$$

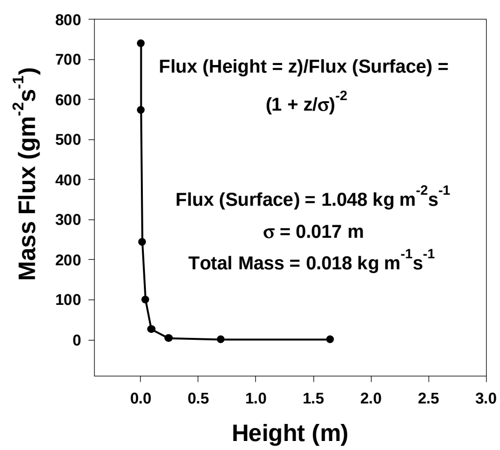
where $f_{max}(z)$ is the maximum horizontal flux at height z (see Eq 2), f_0 is the horizontal surface flux in units of kg m^{-2} s^{-1}, and

transported. Integration of this equation yields an estimate of the total mass flow per unit width of the following form (Stout, 1990a):

$$q \quad f_0 \qquad [4]$$

where q is total mass flow, kg m^{-1} s^{-1} (Fig 9).

Fig 9. Effect of height on sediment mass flux.



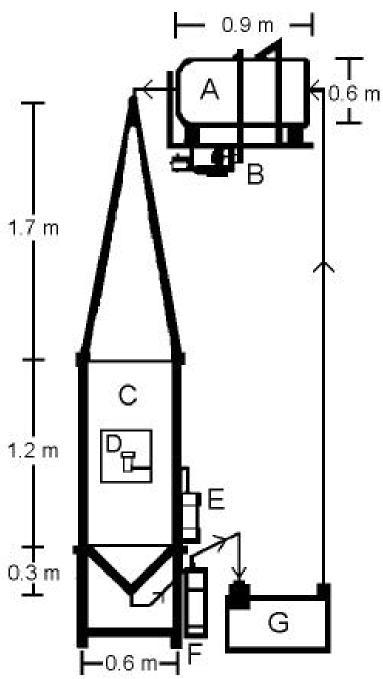
Dust Observations

Dust storms can produce considerable amounts of PM_{10} as measured by air samplers. The US EPA $_{10}$ standard is 150 $^{-3}$. We measured about 375 $^{-3}$ in an eroding agricultural field during a 6.5-hour period of the April 14, 1994 storm at Wolfforth, Texas discussed above (Fig 8). PM_{10} concentrations on wind-eroded agricultural lands of the Columbia Plateau of Washington attained a 12-hour measurements exceeding 10,000 $^{-3}$ September 11, 1993 (Stetler and Saxton, 1996). In contrast, the maximum dust concentrations in non-agricultural lands can be far more severe, exceeding 40,000 $^{-3}$ over several hours at Owens Dry Lake, California (Cahill *et al*., 1996) and perhaps in the hundreds of thousands of $^{-3}$ over many hours in the Sahara (Nickling and Gillies, 1993).

Relating Soils to Dust in the Lab

Field studies relating wind erosion to dust transport can be difficult, impractical and time-consuming. We are developing a system for laboratory measurement of dust produced from field-sampled soils. Its main components consist of a controlled energy dust generator (CE/DG) as described by Singh *et al*. (1994), settling chamber, sampling system and vacuum / forced-air supply (Fig 10).

Fig 10. Dust generating system to measure dust potential.



Legend

A. Controlled Energy Dust Generator (CE/DG)
B. Motor of CE/DG with rotating drive belt
C. Dust settling chamber
D. Observation window and PM_{10} sampling head
E. PM_{10} controller (Minivol)
F. Cyclone dust collector
G. Vacuum / Forced-air supply

Summary

The characterization of airborne dust caused by wind erosion of agricultural fields requires monitoring not only the airborne particles but also the soil surfaces from which they are generated. A number of instruments and techniques are available to monitor both factors. It is important to monitor conditions before and after erosion takes place, as well as during blowing dust events. We have described a system used by the USDA-ARS Wind Erosion Research Unit, Lubbock for monitoring and analysis of wind erosion. Whatever techniques and instruments are used, it is important to make consistent measurements and analyses to provide a useful intercomparison of wind erosion factors between individual sites and erosion events.

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